Solar winds

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Introduction

The sun is losing mass in form of the solar wind, which has affected its evolution from its birth and will continue to do so until its death. This is not unusual in that nearly all stars are losing mass through stellar winds throughout a major portion of their lives. As far as the Earth is concerned, the solar wind blows against the Earth's magnetosphere, causing aurora and geomagnetic storms.

The Corona

The surface of the sun is called the photosphere, above which lies the sun's atmosphere, known as the corona. The solar wind forms in the corona and is caused by high pressure in the corona relative to the low pressure far from the Sun in the interstellar medium. This pressure gradient exerts an outward force against gravity and accelerates the wind from low speeds in the low corona up to supersonic speeds at 5-10 solar radii (R_S). To give a sense of scale, the Earth is 1.5×10^8 km = 215 R_S from the Sun (defined as 1 Astronomical Unit or 1 AU). Typical solar wind speeds beyond 10 R_S are between 300 - 800 km/s so it takes the solar wind 2.2 to 5.8 days to reach Earth. The existence of the solar wind was inferred prior to the space age from the existence of aurora, disturbances to the Earth's magnetosphere, and observations of comet tails. Today it is regularly observed with several spacecraft.

Coronal Expansion

Pressure in the corona is high because the temperature is high, more than 10^6 K, relative to the photospheric temperature of ~5800K. This is a sufficiently high temperature that the corona emits copious X-rays. It is believed that the corona is heated to this high temperature as a byproduct of magnetic field motions, interactions, and instabilities in the photosphere that directly transfer energy into the corona. This energy flux could be via direct heating, waves, jets of material, or other forms, but this is unknown and is the subject of several different observatories in space and a deep space mission called Solar Probe that will travel to within 3 R_S of the photosphere.

The corona is composed mainly of protons and electrons (ionized hydrogen), with minor amounts of silicon, carbon, iron, oxygen, and other elements. There is about 20% helium (by mass) that can be observed spectroscopically, which is how helium was first discovered – thus its name (after Helios, the sun god of Greek mythology). All the components share in the expansion of the corona and can be measured *in situ* by spacecraft outside the earth's magnetosphere.

The sun's magnetic field makes the solar wind far from a simple spherical expansion of a hot gas. The magnetic field is dipole-like but undergoes a reversal during every eleven year solar sunspot cycle. At sunspot minimum the field is aligned with the solar rotation axis while at solar maximum many sunspots appear and the dipole field weakens and becomes irregular. From solar maximum to minimum the field becomes again dipolar, but is inclined relative to the rotation axis. These changes are reflected in changes in coronal structure, which can be seen during solar eclipses such as that shown in Fig. 1. With the bright disk of the sun being occulted by the moon, the faint corona becomes visible, primarily because of light coming from the photosphere being reflected off of electrons in the corona. The areas that are bright are regions of high density and they are known as streamers. The dark regions at the top and bottom in Fig. 1, over the solar rotational poles, are coronal holes. The streamers in Fig.1 lie over the magnetic equator and the density is higher because ions and electrons are trapped on closed loops of the dipolar magnetic field. The low density coronal holes mark the locations of the north and south magnetic poles. Fig. 1 was taken in 1994, just prior to solar minimum so that the magnetic axis was inclined to the rotational axis that is towards the top of this image.

Fig. 2 is a schematic drawing of the stages of coronal evolution over the eleven year sunspot cycle, starting at solar maximum on the left. Fig.1 is represented by the drawing in Fig.2(c). The magnetic field loops in streamers are shown here to help suggest why the ions and electrons are trapped, just as iron filings tend to align along magnetic field lines around a bar magnet. Coronal holes are shown by the dark areas on the solar disk. This figure also indicates that fast solar wind originates from coronal holes and slow solar wind from above streamers. Fast solar wind has speeds above ~600 km/s at 1 AU and slow solar wind has speeds below ~500 km/s. This division into fast and slow wind could be observed if one were able to pass around the sun as shown in Fig.2(c) from south pole to north pole. It would then be possible to sample first fast wind from the south pole, slow wind from over the equatorial streamers, and then fast wind again from the north pole. The Ulysses spacecraft carried out this exercise in 1995-1996 at solar sunspot minimum and a plot of the observed solar wind speed is shown in Fig.3 using what is called a dial plot. The dial plot indicates the solar latitude around the origin and the measured solar wind speed as distance from the origin. The fast wind in the north and south is very clearly divided from the slow wind above the equatorial streamers in this plot. This demonstrates one of the major discoveries in recent years - that fast and slow solar wind represent two distinct states between which there is no continuous change. Fast wind comes from coronal holes and is rather smooth and uniform at 1 AU. Conversely, slow wind is relatively irregular and comes either from thin boundaries around streamers or leaks somehow from within streamers. Fig.4 shows profiles of how fast and slow wind vary with distance from the sun, illustrating that not only are the speeds different but that there are also characteristic densities and temperatures differences. T_e and T_p are the proton and electron temperatures in this plot. The distinct difference between the two solar wind states leads to important consequences because of solar rotation.

Solar Rotation and the Magnetic Field in the Solar Wind

Solar wind is an ionized gas made up primarily of protons and electrons with minor ions in amounts similar to those in the corona. The electrons and ions are very tightly bound to lines of magnetic flux, again like the coronal plasma in streamers. However, the magnetic field in the solar wind is relatively weak and thus is carried along by the solar wind. The rotation of the sun results in the lines of magnetic flux in the solar wind being drawn into Archimedian spirals. This is because the Sun revolves once every ~25.5 days while, as mentioned above, it takes solar wind several days to reach 1 AU. Therefore the sun revolves through a significant angle during the time it takes the solar wind to reach the Earth. For example, taking a typical speed of 400 km/s, it takes solar wind 4.34 days to reach 1 AU. During the same time, the sun will have revolved through about 60 degrees, or about 1/6 of a full rotation. The magnetic field in the solar wind, called the interplanetary magnetic field, or IMF, is attached to the sun at the point where the solar wind began. Thus, the point on the field line attached to the sun is turned through an angle of 60 degrees relative to the point on the magnetic field line that is at 1 AU. The field line between the sun and 1 AU traces a continuous curve between these two points. Assuming the solar wind speed, v (km/s), is independent of distance from the sun, this curve is described by

$$r - r_o = \frac{-v}{\Omega \cos\theta}(\phi - \phi_o) \tag{1}$$

In (1), r is the distance from the center of the sun in km, r_o=6.96x10^5 km = the radius of the sun, Ω=2.85x10^{-6} s^{-1} is the angular velocity of the sun, and (ϕ-ϕ_o) is the difference in longitude (in radians) at the two points on the field line. θ is solar latitude and the Earth lies in the range -7.25<θ<7.25 degrees since the plane of the ecliptic is inclined to the solar equator by 7.25 degrees. The angle (ϕ-ϕ_o) is also the angle between the magnetic field line and the radial direction at 1 AU, or wherever (1) is evaluated. This is called the spiral angle. The geometry of the curved field line is precisely an Archimedian spiral when v is constant and is one of the important predictions made by E. Parker when he developed his theory for the solar wind in the 1950s and 1960s. Fig.5 illustrates two spirals computed using (1). The tighter spiral above results from low speeds, <500 km/s, and the spiral angle is >45 degrees at 1 AU. Conversely, the spiral angle at 1 AU is <45 degrees for speeds >500 km/s. Parker predicted that (ϕ-ϕ_o)~45 degrees (0.785 radians) at 1 AU and this is what has been measured for the average spiral angle by several different spacecraft.

Corotating Interaction Regions

Solar rotation has an important effect on coronal expansion through the interaction of fast and slow wind. During the declining phases of the solar cycle, Fig.2(b), regions on the sun producing slow wind will sometimes face the Earth and at other times regions producing fast wind will face the Earth. Thus it will often be the case, especially during declining phases of the solar cycle, that slow wind will be followed by fast wind. This is just the example diagrammed in Fig.5. When this happens, fast wind overtakes slow wind, the gas in between becomes compressed, and eventually shocks form with forward shocks moving away from the sun and reverse shocks moving towards the sun in the frame of reference moving with the solar wind. This is called a corotating interaction region (CIR) because it appears stationary in the frame of reference rotating with the sun. As the plasma between the fast and slow wind becomes compressed, the velocity profile is dynamically altered and the CIR becomes stronger and stronger with increasing distance until the shocks forms. A simple estimate for where the shocks will form can be made using

$$r - r_o = \frac{v_1 v_2}{v_2 - v_1} \frac{(\phi_2 - \phi_1)}{\Omega \cos\theta} \tag{2}$$

where the same definitions are used as in (1). The quantity (ϕ_2-ϕ_1) is the difference in longitude of the source regions of fast and slow wind, v_1 and v_2 are the slow and fast wind speeds, respectively, and r is the estimated distance for shock formation. Taking (ϕ_2-ϕ_1)=0.53 radians=30 degrees, v_1=400 km/s, and v_2=800 km/s gives r=1.5x10^8 km = 1 AU. During the declining phases of the solar cycle it is observed that shocks generally form around 2 AU which is consistent with (2) since (ϕ_2-ϕ_1) is more nearly 1 radian that 0.5 radians at those times. Forward shocks are rarely observed at 1 AU and reverse shocks are only observed in ~20% of CIRs at 1 AU. Equation (2) was derived simply by calculating when the two field lines shown in Fig.5 would cross. These field lines are the same as the streamlines in the frame of reference corotating with the sun and this is why (2) looks closely related to (1).

CIRs have a very distinctive character as seen in the long series of CIRs observed by Ulysses in 1992 when it was near the sun's equator. About five solar rotations of the data are shown in Fig.6. At the time Ulysses was at ~4 AU and fast wind had overtaken slow wind to form shocks where the speed is seen to abruptly jump upwards as time progresses from left to right. CIRs have important consequences for the Earth since they can produce auroral activity and magnetic storms when they strike the Earth's magnetosphere if the IMF is also directed southward so that it can easily merge with the Earth's magnetic field. CIR associated magnetic storms naturally tend to reoccur every solar rotation – 27 days as viewed from the Earth due to the Earth's motion around the sun. This activity also has a distinct solar cycle signature as the sun moves through the phases diagrammed in Fig.2. Thus, observation of coronal holes and streamer and the phase of the solar cycle provides a basic tool for the prediction of space weather and geomagnetic activity. A further consequence of CIRs is that the resulting shock waves produce large numbers of high energy particles or cosmic rays. These particles affect the Earth's ionosphere and the radio communications that depend on the ionosphere.

Coronal Mass Ejections

Up to this point, a picture of the solar wind has been drawn that depicts it as quasi-steady, changing only slowly over the eleven year solar sunspot cycle. This is not an accurate picture at any time, especially near solar maximum. There are many forms of solar activity, including flares and erupting prominences, but the most dramatic drammatic is the release of a coronal mass ejection, or CME. A picture of a CME is shown in Fig.7. This picture was taken from the SOHO spacecraft using a telescope called LASCO which places an occulter over the solar disk so that the corona becomes visible, producing an artificial solar eclipse. The occulter is twice the size of the sun, and the disk of the sun is indicated by the white circle. Off to the lower right of the image is the CME. These are seen throughout the entire solar cycle, but they are 5-10 times more common near solar maximum, occurring at a rate of 3-4 per day. They occur in and near streamers, confined to low latitudes near solar minimum but reaching all latitudes at solar maximum.

When an interplanetary CME (ICME) strikes the earth, the consequences are similar to those of a large CIR. The magnetosphere is compressed, auroral activity increases, and a magnetic storm or substorm may occur if the IMF in the ICME is directed southward. Ionospheric activity is also affected. This is therefore a phenomenon which is actively monitored in the context of space weather.

One CME is visible in the data shown in Fig.6. At about 10 November 1992 the solar wind speed increases to ~1000 km/s. This is above any speed for simple fast solar wind. Instead, what is seen here is a fast ICME that has overridden a CIR. This could have a doubly strong impact on the magnetosphere due to the large speed enhancement.

ICMEs are another phenomenon in the solar wind that is only partially understood. The propagation of an ICME can be modeled fairly well using computers and a numerical solution to the equations of motion. However, the basic mechanisms causing the initiation of a CME are not known. CMEs are related to solar magnetic activity such as flares and erupting prominences but that relationship is not so simple that one can predict a CME for anything except the very largest of these events.

The Solar Wind Over the Life of the Sun

The IMF is not completely passive in the solar wind. Because it is attached to the sun, and has a small, but finite strength, the IMF tends to cause the solar wind to rotate with the sun out to some distance above the photosphere. In doing this, the IMF causes angular momentum of the sun to be transferred to the solar wind. Generally this is a small effect, with the corotation distance being 10-20 R_S at most, or 0.1 AU. However, over the life of the sun, the effect can be important. Calculations of the angular momentum transfer suggest that the present-day solar wind and IMF could easily have doubled the rotation period of the sun, from 12.25 to 25.5 days, over the 4.5 billion year life of the sun.

Presently the solar wind only carries away a very small amount of mass from the sun, so small that if assumed the same for 4.5 billion years it would have removed only ~0.01% of the total mass of the sun. However, the sun changes over its life, as do all stars. The sun probably had a very vigorous wind early in its life when the solar convection zone extended throughout the entire volume of the sun. Later, the sun will go through a red giant phase, expanding outward to envelop the earth, and the wind may again become quite strong. If the sun undergoes a catastrophic collapse to form a white dwarf then there may be one or several episodes of impulsive mass ejection call novae. However, the sun is a relatively small and inactive star – other stars can have quite different and often far more intense winds.

Winds From Other Stars

Stellar winds are, as indicated above, common. One way they are detected and analyzed is through Doppler shifts in spectral lines. Another way is to infer the presence of the wind through analysis of properties of the associated star. Stellar winds found this way are all far stronger than the solar wind but the reader should be cautioned that this is an observational selection effect. The sun's wind would be invisible at stellar distances. If all stars were like the sun, we would presently have no way to directly detect their winds. However, many stars are larger, hotter, denser, rotate faster, have stronger magnetic fields, are younger, or are older than the sun and consequently have quite different kinds of winds. They fall into several categories that are in addition to winds like the solar wind that are primarily driven by a thermal pressure gradient.

Sound wave driven winds

In stars with a convection zone just below the photosphere, the convective motions can generate acoustic waves which propagate upwards through the photosphere. The waves produce a wave pressure in the atmosphere that results in an additional force working against the stellar gravity. Cool stars have convection zones of this type but it is normally important only for very low gravity stars. To make a massive wind requires something else in addition to sound waves because sound waves will normally dissipate low in the stellar atmosphere. The dissipation of sound waves heats the atmosphere so that there can be some cross-over between thermally driven winds and sound wave driven winds.

Dust driven winds

The outer atmospheres of luminous cool giant stars and early-type stars can be driven outward by radiation coming from the photosphere of the star. In the case of cool stars, dust can condense out of the atmosphere and absorb photons over a broad range of wavelengths. The radiation pressure forces the grains outward, dragging ions along by viscous drag if the atmosphere is dense, thus forming a dust driven wind.

Alfvén wave driven winds

Alfvén waves are waves dominated by fluctuations transverse to the magnetic field direction. The restoring force is the resistance of the magnetic field to forming a kink, as opposed to the resistance of a gas to being compressed in sound waves. These waves are more important for stars with stronger magnetic fields. The dissipation of energy and momentum associated with Alfvén waves can lead to the acceleration of a wind, just as in sound wave driven winds. The waves are formed by motions in the photophere causing the magnetic field line to be moved. Alfvén waves have been suggested to be one source of the energy flux driving the solar wind. However, it is not yet known whether this is the dominant energy source. The dissipation of Alfvén waves will heat the atmosphere and increase the thermal pressure so that there is also some cross-over between thermally driven winds and Alfvén wave driven winds.

Radiation pressure driven winds

In these winds, atoms in the atmosphere of the star resonantly absorb radiation coming from the photosphere of the star. As might be expected, these winds exist for stars that are brighter and hotter than the sun. Instead of 10^{-4} solar masses being lost over the life of the star, these stars can loose 10^{-6} solar masses in a single year. The flow speeds are typically ~2000 km/s and the density in these winds is many orders of magnitude higher than in the solar wind. The higher density means that the atmospheres of these stars are far more opaque than the solar corona. This is what enables them to absorb the radiation coming from the star. In this case the radiation pressure is the force which is working against the gravitational field of the star. The force ceases once the atmosphere becomes transparent as distance from the star increases. In red giant stars the radiation intensity is relatively weak but the gravitational field is also weak and the stars are nevertheless observed to have radiatively driven winds. However, the strongest radiatively driven winds come from hot supergiants.

Magnetic rotator winds

In discussing the solar wind over the lifetime of the sun we described how the magnetic field enhances the loss of angular momentum from the sun by causing the ions and electrons to rotate together with the sun as they move outward. At the same time, there is also a small outward centrifugal force, just as there is in a centrifuge. This force is completely negligible for the sun but one can imagine stars with stronger magnetic fields that might have centrifugally driven winds – called magnetic rotator winds.

The most obvious example of a magnetic rotator wind is that from a neutron star. These stars have very strong magnetic fields and centrifugal forces fill the neutron star magnetosphere with charged particles. At some distance from the star, the azimuthal velocity of the charged particles, as they are carried around the star, reaches the speed of light. This is the speed of light cylinder and somewhere in this region around the star the particles force the field lines to open and they are released. This is how a pulsar is formed – an extreme example of a magnetic rotator.

Effects of winds on stellar evolution and on the surrounding interstellar medium

Winds from stars are one way matter that has been processed in stellar interiors reaches the interstellar medium and becomes available for new star formation – the other way being novae and supernovae. The composition of the wind reflects, but may not be identical to, the composition of the star. Primordial material will be processed and enriched in heavy elements in this process.

The solar wind serves as an example of this process, even though the wind is relatively weak. The wind moves outward to interact with interstellar material that is always present in the galaxy. There is a contact surface that divides interstellar material from solar wind and the volume inside this surface is known as the heliosphere – that volume dominated by the sun. The solar system is moving through the local interstellar medium at ~25 km/s – slow with respect to solar wind speeds – and the stand-off distance in the upstream direction is about 150 AU. Beyond this boundary lies pristine interstellar matter. In the downstream direction the solar wind flows into a heliotail that is analogous to the earth's magnetotail and is the path by which the solar wind escapes and mixes with interstellar matter.

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See also: **Convection (120), Atmospheric electricity global circuit (144), Ionosphere (184), Magnetosphere (211), Protonosphere/geocorona (325), Solar Radiation (334), Satellite orbits (362), Solar cycle (368), Solar terrestrial climate impact (369), Solar terrestrial energy deposition (370), Solar atmosphere (371), Solar variability (372), Space weather (376), Tropospheric Nox (431), Tropospheric ozone chemistry & processes (421), Tropospheric ozone observations and structure (420).**

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Key Words: Solar Wind, Corona, Stellar Winds, Alfvén Waves, Sun, Solar Cycle, Space Weather, Solar Terrestrial Interactions, Magnetic Storms.

List of Nomenclature, Terms, and Units:

Alfvén Wave : A bending wave in a magnetic field in which the restoring force is due to the curvature of the magnetic field. Named after Hannes Alfvén, the Nobel prize-winning scientist who discovered the wave.

AU : “Astronomical Unit.” The mean distance of the Earth from the sun, 1.5×10^8 km.

CIR : “Corotating interaction region.” The dynamic interaction that occurs when fast solar wind catches up with and compresses preceding slow solar wind. See Fig. 5.

CME : “Coronal mass ejection.” See Fig.7.

Heliosphere : The volume of space containing solar wind, as opposed to the interstellar medium, which is the milky way galaxy outside the heliosphere.

IMF : “Interplanetary Magnetic Field.” The magnetic field that is trapped in and carried along with the solar wind.

LASCO : “Large Angle Spectroscopic COronagraph.” A coronagraph on the ESA/NASA SOHO mission.

Photosphere : The visible surface of the sun.

Radian : A measure of angular distance. There are 2π radians in a circle.

R_S : Radius of the sun, 6.96×10^5 km.

SOHO : “SOlar-Heliospheric Observatory.” A joint ESA and NASA spacecraft located at the L1 Lagrangian point between the sun and the earth, about 1/100th AU towards the sun from the earth.

Solar Probe : A future NASA mission to the Sun. Solar Probe is designed to go within 3 R_S of the photosphere.

Ulysses : A spacecraft in a near-polar five-year orbit around the sun.

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Figure Legends:

Figure 1: Total solar eclipse as seen from Putre, Chile on 3 November 1994 (Photo courtesy of High Altitude Observatory, National Center for Atmospheric Research).

Figure 2: Schematic illustration of the three stages in the eleven year solar sunspot cycle. (a) Solar maximum when the corona is filled with streamers and there are few or no coronal holes. There is no well defined large scale field. (b) Declining phases when the large scale field is dipole-like and inclined to the heliographic equator. (c) Solar minimum when the field is dipolar, aligned with the rotation axis, and when the polar coronal holes are largest.

Figure 3: Dial plot of solar wind speed, indicated by radial distance from the origin, as a function of heliographic latitude, measured around the origin of the plot. Data were collected by the Ulysses solar wind plasma instrument between September 1994 and July 1995, during which time Ulysses swept from 80° south latitude to 80° north latitude.

Figure 4: Solar wind flow speed, density, and temperature between 2 and 100 R_S, for coronal holes (gray lines) and streamers (black lines). These are typical values, with the possible range around these values being quite large.

Figure 5: Diagram of spiralling interplanetary magnetic field (IMF) lines. The dependence on solar wind speed is illustrated by the more curved line at the top being for relatively slow wind and the less curved line at the bottom being for fast wind.

Figure 6: Solar wind speed at Ulysses during August – December 1992 when Ulysses was near the heliographic equator and at ~5 AU. Five corotating interaction regions (CIRs) are shown, occurring approximately every 25.5 days or each solar rotation. Viewing the plot from left to right, each CIR is characterized by a sharp speed increases at forward and reverse shocks at the front of the CIR, followed by the speed maximum. The speed then decreases down to a minimum before increasing in the next CIR. The very high speed on 10 November 1992 is due to a coronal mass ejection on top of the CIR.

Figure 7: A coronal mass ejection is seen in the lower right quadrant in this image from the LASCO coronagraph on SOHO. The sun, which is covered by an occulter that is 4 R_S in diameter, is indicated by the white circle.

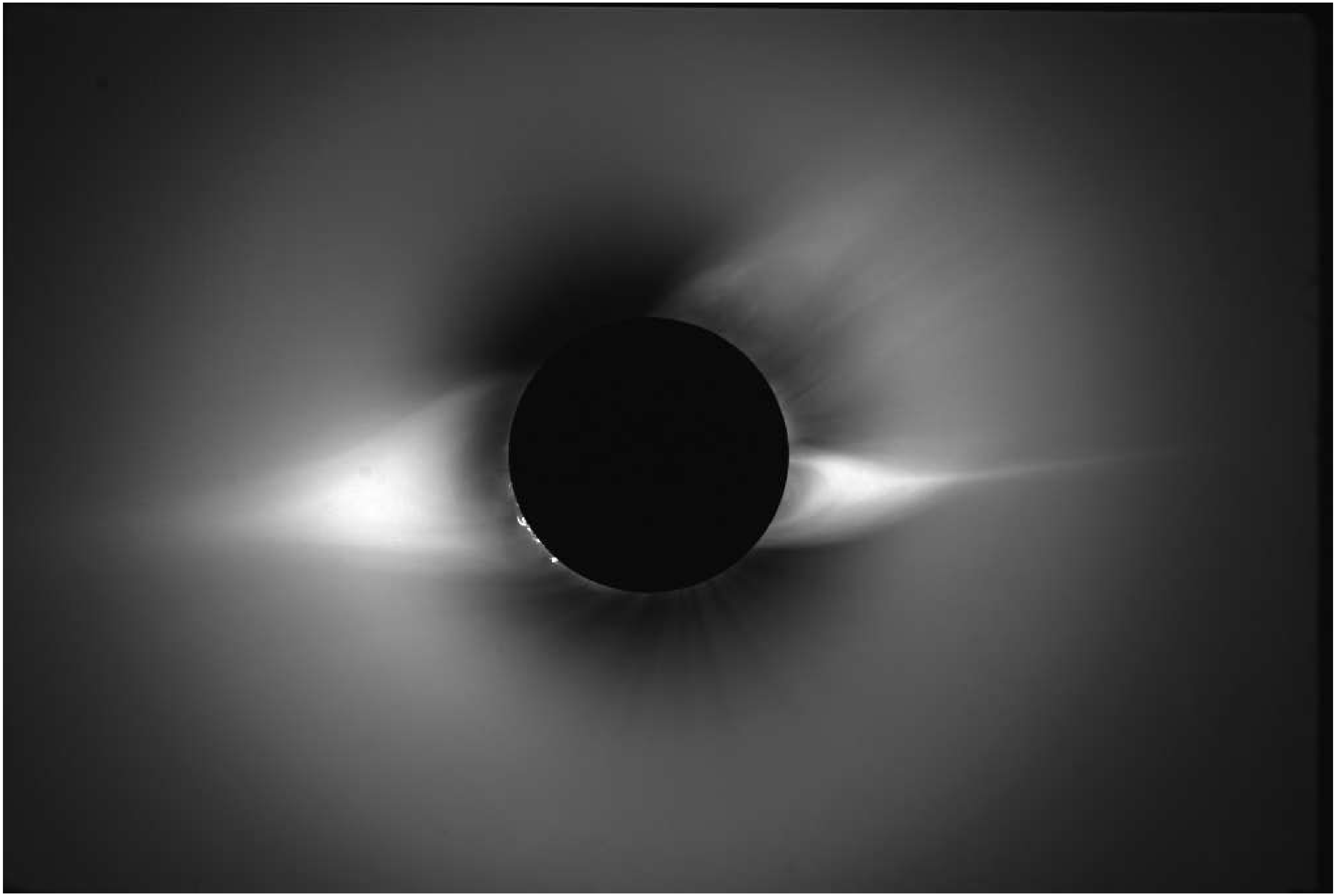

Fig. 1
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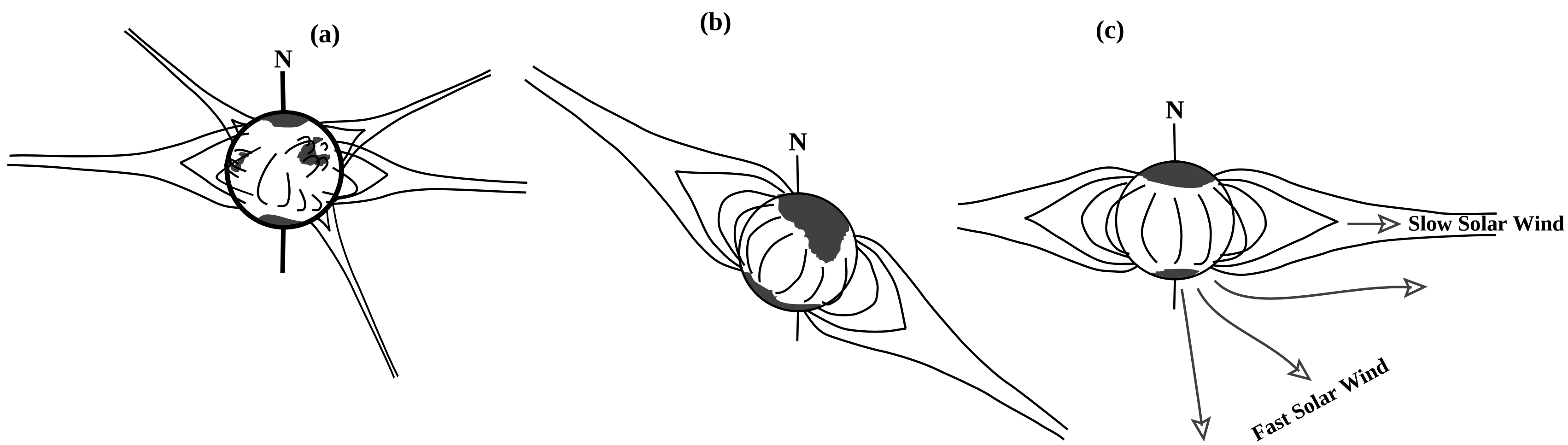

Fig. 2
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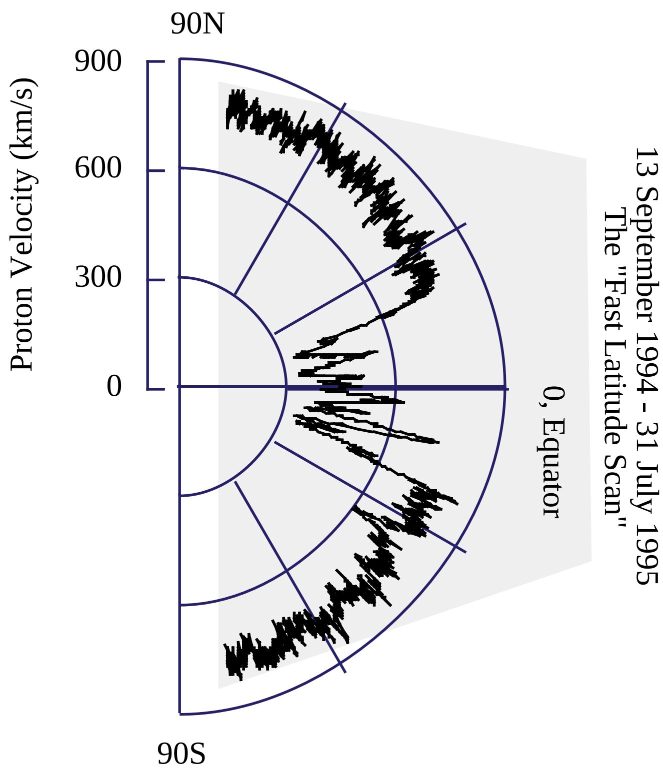

Fig. 3
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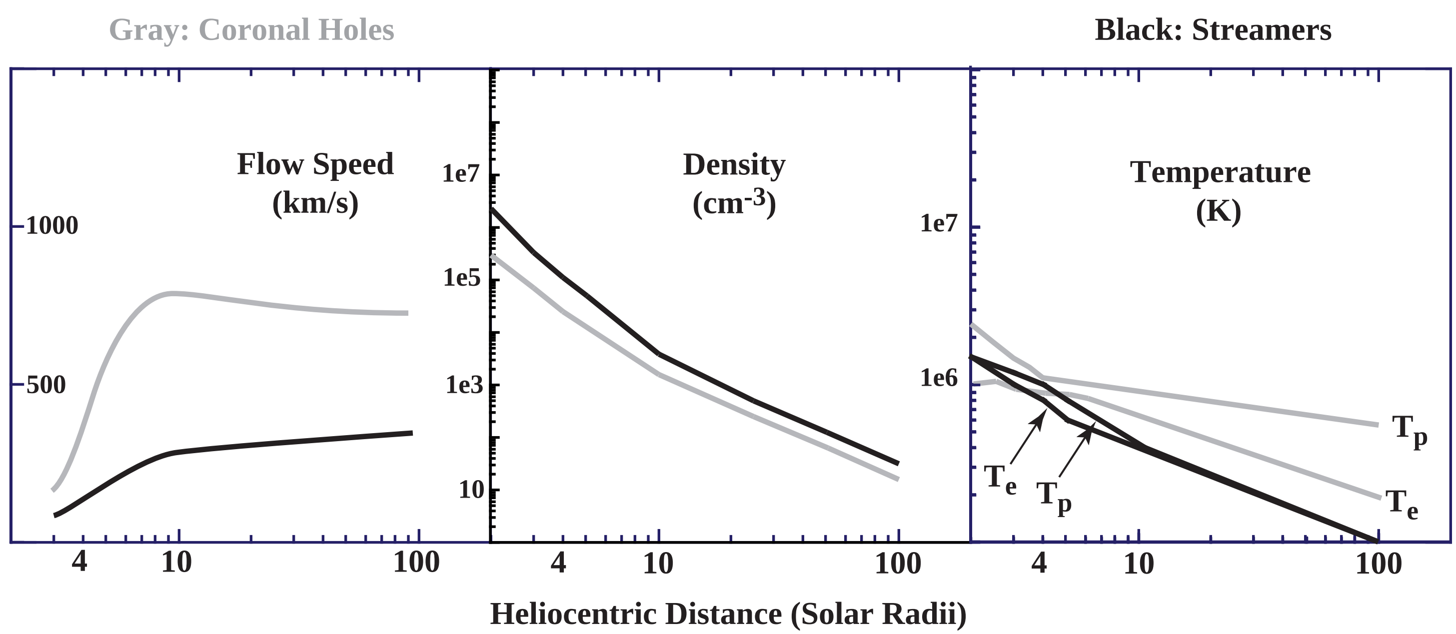

Caption: Solar wind properties in thefast (gray lines) and slow (black lines) solar wind.

Fig. 4
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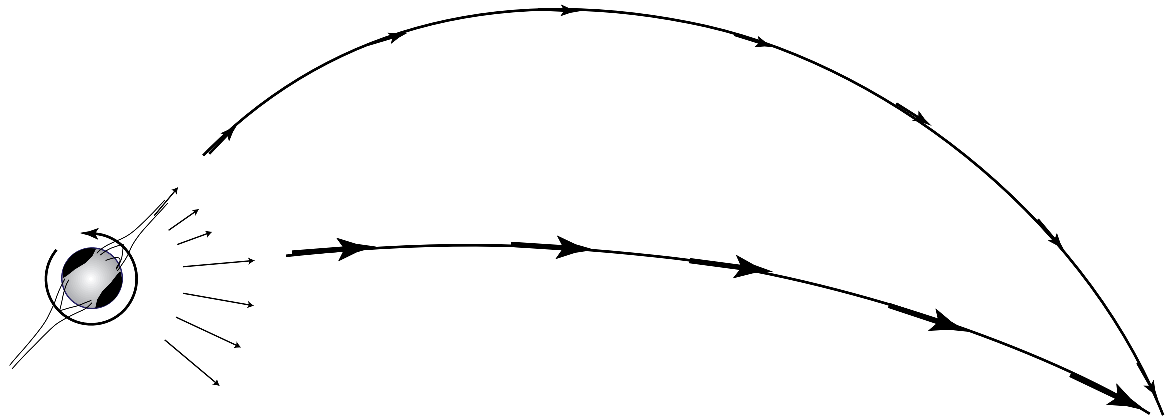

Fig. 5
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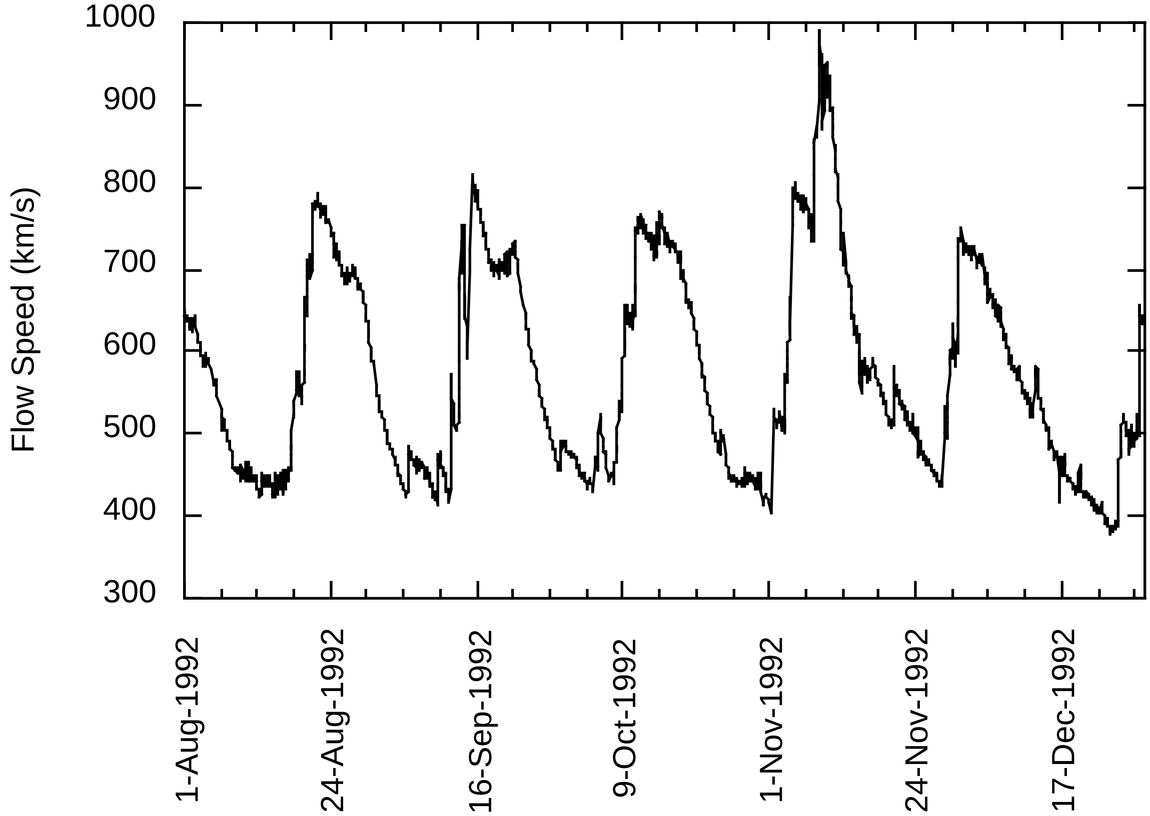

Fig. 6
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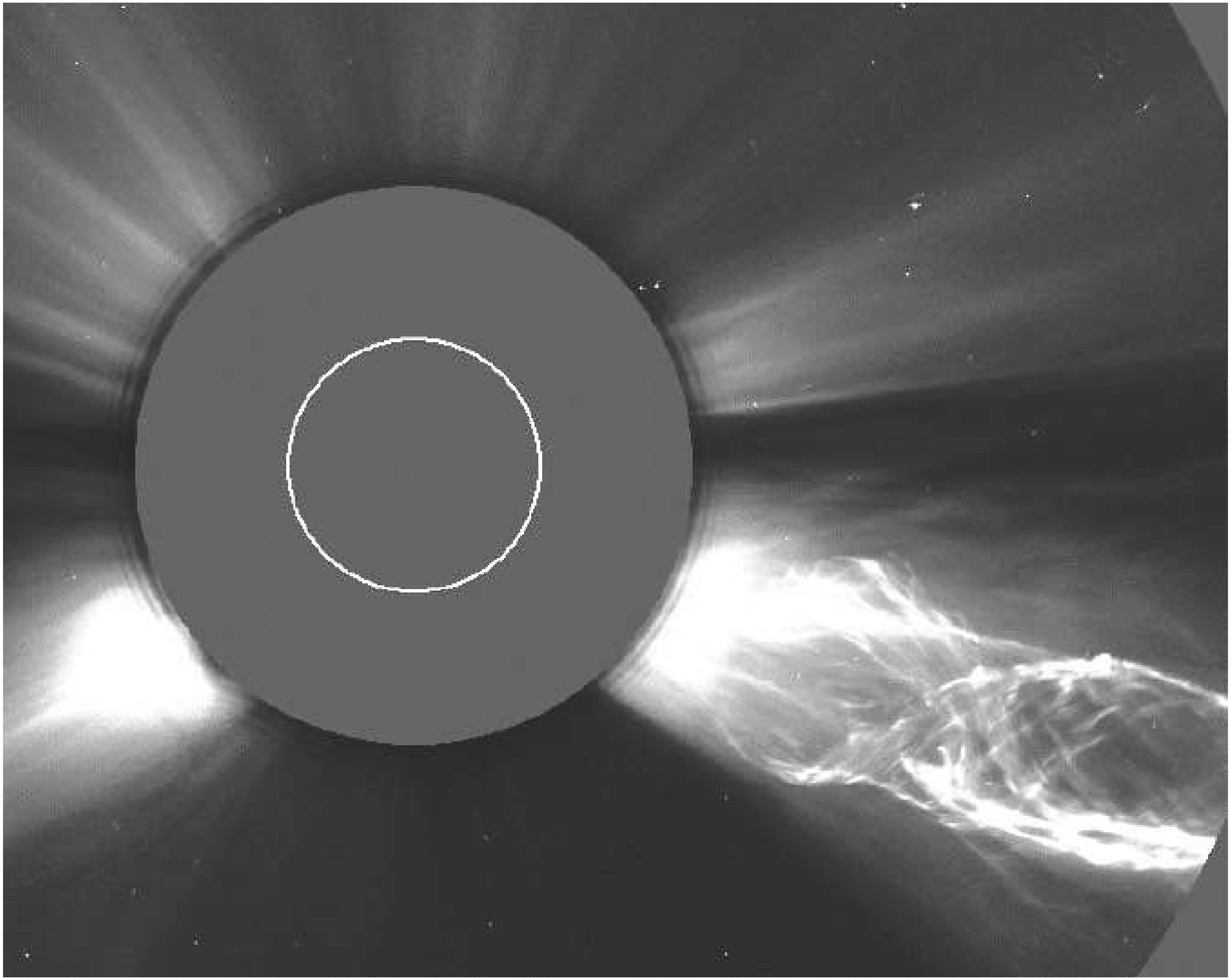

Fig. 7
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